GC-122..S-U1

Patent Application

for:

IMPROVED, MANUFACTURABLE SAMPLED GRATING MIRRORS

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Express Mail No.: ET103178994US

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit under 35 U.S.C. Section 119(e) of the following co-pending and commonly-assigned U.S. provisional patent application: Serial No. 60/210,612, filed June 9, 2000, by Gregory A. Fish and Larry A. Coldren, entitled "IMPROVED, MANUFACTURABLE SAMPLED GRATING MIRRORS," attorneys' docket number 122.3-US-P1, which application is incorporated by reference herein.

This application is related to the following co-pending and commonly-assigned U.S. utility patent applications:

Serial No. 09/614,224, filed July, 12, 2000, by Larry A. Coldren et al., and entitled "METHOD OF MAKING A TUNABLE LASER SOURCE WITH INTEGRATED OPTICAL AMPLIFIER";

Serial No. 09/614,377, filed July, 12, 2000, by Larry A. Coldren, and entitled "INTEGRATED OPTO-ELECTRONIC WAVELENGTH CONVERTER ASSEMBLY";

Serial No. 09/614,376, filed July, 12, 2000, by Larry A. Coldren et al., and entitled "METHOD OF CONVERTING AN OPTICAL WAVELENGTH WITH AN OPTO-ELECTRONIC LASER WITH INTEGRATED MODULATOR";

Serial No. 09/614,378, filed July, 12, 2000, by Larry A. Coldren et al., and entitled "OPTO-ELECTRONIC LASER WITH INTEGRATED MODULATOR";

Serial No. 09/614,895, filed July, 12, 2000, by Larry A. Coldren, and entitled "METHOD FOR CONVERTING AN OPTICAL WAVELENGTH USING A MONOLITHIC WAVELENGTH CONVERTER ASSEMBLY";

Serial No. 09/614,375, filed July, 12, 2000, by Larry A. Coldren et al., and entitled "TUNABLE LASER SOURCE WITH INTEGRATED OPTICAL AMPLIFIER";

Serial No. 09/614,195, filed July, 12, 2000, by Larry A. Coldren et al., and entitled "METHOD OF MAKING AND OPTO-ELECTRONIC LASER WITH INTEGRATED MODULATOR";

Serial No. 09/614,665, filed July, 12, 2000, by Larry A. Coldren et al., and entitled "METHOD OF GENERATING AN OPTICAL SIGNAL WITH A TUNABLE LASER SOURCE WITH INTEGRATED OPTICAL AMPLIFIER"; and

Serial No. 09/614, 674, filed July, 12, 2000, by Larry A. Coldren, and entitled "METHOD FOR MAKING A MONOLITHIC WAVELENGTH CONVERTER ASSEMBLY";

all of which are incorporated by reference herein, all of which claim priority to each other, and all of which claims the benefit under 35 U.S.C. §119(e) to the following U.S. provisional patent applications:

Serial No. 60/152,038, filed on September 2, 1999, by Gregory Fish et al., and entitled "OPTOELECTRONIC LASER WITH INTEGRATED MODULATOR";

Serial No. 60/152,049, filed on September 2, 1999, by Larry Coldren, and entitled "INTEGRATED OPTOELECTRONIC WAVELENGTH CONVERTER"; and

Serial No. 60/152,072, filed on September 2, 1999, by Beck Mason et al., and entitled "TUNABLE LASER SOURCE WITH INTEGRATED OPTICAL AMPLIFIER".

BACKGROUND OF THE INVENTION

1. Field of the Invention.

The present invention relates generally to wide-range tunable semiconductor lasers and particularly to sampled-grating distributed Bragg reflector (SGDBR) lasers. More particularly, this invention relates to an improved design for sampled grating distributed Bragg reflector (DBR) mirrors.

2. Description of the Related Art.

Diode lasers are being used in such applications as optical communications, sensors and computer systems. In such applications, it is very useful to employ lasers that can be easily adjusted to output frequencies across a wide wavelength range. A diode laser which can be operated at selectably variable frequencies covering a wide wavelength range, i.e. a widely tunable laser, is an invaluable tool. Such a "widely-tunable" laser enables real-time provisioning of bandwidth, and a much simplified sparing scheme. By including widely-tunable lasers in a system, if one laser malfunctions, a spare channel, purposely left unused, may be configured to the wavelength of the malfunctioning laser and ensure the proper function of the system.

Thus, while diode lasers have provided solutions to many problems in communications, sensors and computer system designs, they have not fulfilled their potential based on the available bandwidth afforded by light-based systems. It is important that the number of channels be accessed and switched between in order for optical systems to be realized for many future applications.

For a variety of applications, it is necessary to have tunable single-frequency diode lasers which can be quickly configured to emit coherent light at any of a wide range of wavelengths. Such applications include sources and local oscillators in coherent lightwave communications systems, sources for other multi-channel lightwave communication systems, and sources for use in frequency modulated sensor systems. Continuous tunability is usually needed over some range of wavelengths. Continuous tuning is important for wavelength locking or stabilization with respect to some other reference, and it is desirable in certain frequency shift keying modulation schemes.

In addition, widely tunable semiconductor lasers, such as a sampled-grating distributed-Bragg-reflector (SGDBR) laser, a grating-coupled sampled-reflector (GCSR) laser, and vertical-cavity surface emitting lasers with micro-electromechanical moveable mirrors (VCSEL-MEMs) generally must compromise their output power in order to achieve a large tuning range. Designs that can provide over 40 nm of tuning range have not been able to provide much more than a couple of milliwatts of power out at the extrema of their tuning spectrum. However, current and future optical fiber communication systems as well as spectroscopic applications require output powers in excess of 10 mW over the full tuning band. Current ITU bands are about 40 nm wide near 1.55 μm and comprise the c-band, s-band and L-band, and it is desired to have a single component that can cover at least one or more of these bands.

Systems that are to operate at higher bit rates may require more than 20 mW over the full ITU bands. Such powers are available from DFB lasers, but these can only be tuned by a couple of nanometers by adjusting their temperature. Thus, it is very desirable to have a source with both wide tuning range (> 40 nm) and high power (> 10 mW) without a significant increase in fabrication complexity over existing widely tunable designs.

One path to achieving high output power and wide tuning ranges, is to improve upon the conventional sampled grating mirrors or reflectors (which shall be used interchangeably hereinbelow). Figure 1 shows a typical reflectivity spectrum from a pair of mirrors used within a SG-DBR laser. The design of the SG-DBR is constrained by the desired tuning range, output power and side-mode suppression. It is impossible to simultaneously maximize all three of the above specifications using a SG-DBR, as improving one specification worsens the others. The major concerns when designing a multi-peaked mirror are to achieve the desired coupling constant (κ) and reflectivity (R) for each peak.

The sampled grating approach is limited largely by the fact that the unsampled grating κ is technologically limited by optical scattering to around 300 cm^{-1}. Another limiting factor is that the reflectivity of the multi-peaked mirror falls off at the outer peaks, along with the gain. Therefore, it is desirable to increase the effective κ of each peak as well as compensate for any loss in gain with increased reflectivity. In order to increase the κ of the SG mirror peaks, the sampling duty ratio (the length of sampled portion divided by the sampling period) must also increase. This duty ratio, however, is inversely proportional to the wavelength range the multi-peaked SG mirror can effectively cover, which limits the tuning range of a SG-DBR laser.

Therefore, what is needed in the art is a sampled grating mirror that covers a wide tuning range with the desired κ, as well as having mirror peaks that do not have substantial power dorpoffs at the edges of the band.

SUMMARY OF THE INVENTION

To address the issues described hereinabove, enhanced sampled-grating distributed Bragg reflector (SGDBR) mirrors are disclosed and taught in accordance with the present invention. The major concerns when designing a SGDBR or multi-peaked mirror are to achieve the desired coupling constant (κ) and reflectivity (R) for each peak. The explicit details of the mirror design with respect to these values are described in U.S. Patent No. 4,896,325, issued January 23, 1990, to Larry A. Coldren, entitled "MULTI-SECTION

TUNABLE LASER WITH DIFFERING MULTI-ELEMENT MIRRORS", which patent is incorporated by reference herein.

Several references describe structures and methods for achieving wide tuning ranges. These references include:

V. Jayaraman, A. Mathur, L.A. Coldren and P.D. Dapkus, "Theory, Design, and Performance of Extended Tuning Range in Sampled Grating DBR Lasers," *IEEE J. Quantum Elec.*, v. 29, (no. 6), pp. 1824-1834, (June 1993);

H. Ishii, H. Tanobe, F. Kano, Y. Tohmori, Y. Kondo, Y. Yoshikuni, "Quasicontinuous Wavelength Tuning in Super-Structure-Grating (SSG) DBR Lasers", *IEEE J. Quantum Elec.*, v. 32, (no. 3), pp. 433-441, (March 1996);

I. Avrutsky, D. Ellis, A. Tager, H. Anis, and J. Xu. "Design of Widely Tunable Semiconductor Lasers and the Concept of Binary Superimposed Gratings (BSG's)", *IEEE J. Quantum Elec.*, v. 34, (no. 4), pp. 729-741, (April 1998);

B. Mason, G.A. Fish, S.P. DenBaars, and L.A. Coldren, "Widely Tunable Sampled Grating DBR Laser with Integrated Electroabsorption Modulator," *Photon. Tech. Letts.*, 11, (6), 638-640, (June 1999); and

Tennant, D.M., Koch, T.L., Verdiell, J.-M., Feder, K., Gnall, R.P., Koren, U., Young, M.G., Miller, B.I., Newkirk, M.A., Tell, B., *Journal of Vacuum Science & Technology B* vol.11, (no.6), Nov.-Dec. 1993. p.2509-13.

Each of the proceeding references are incorporated herein by reference, however, they fail to teach or suggest the present invention.

The present invention comprises a specially configured DBR mirror. And such a mirror may be included in a tunable laser. The tunable laser generally comprises a gain section for creating a light beam by spontaneous emission over a bandwidth, a phase section for controlling the light beam around a center frequency of the bandwidth, a waveguide for guiding and reflecting the light beam in a cavity, a front mirror bounding an end of the cavity and a back mirror bounding an opposite end of the cavity wherein gain is provided by at least one of the group comprising the phase section, the front mirror and the back mirror.

This invention relates to the tailoring the reflectivity spectrum of a SGDBR by applying digital sampling theory to choose the way each mirror is sampled. The resulting

mirror covers a larger wavelength span and has peaks with a larger, more uniform, coupling constant (κ) than the mirrors produced using conventional approaches. The improved mirror also retains the benefits of the sample grating approach. These embellishments on the SGDBR design provide devices that meet the higher power goals with wide tuning. In addition, most of the embodiments are relatively simple to manufacture.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

Fig. 1 Shows a schematic of a SG-DBR laser illustrating the use of two sampled grating reflectors to form the laser resonator containing a gain and phase shift region.

Fig. 2 illustrates the typical reflectivity spectrum of a sampled-grating mirror showing the multiple peaks and the decrease of the reflectivity at the edges of the spectrum.

Fig. 3 (a) & (b) illustrates a schematic diagram and the mathematical representation of the sampled grating reflector. The representation can be thought of the multiplication of grating function and a sampling function.

Fig. 4 gives an example of a very simple modification to the conventional grating that could be used to tailor the envelope of the peak mirror reflectivities, in which a burst of anti-phased grating is positioned properly in front of the 1st burst of the conventional grating.

Fig. 5 shows a simulation illustrating the effect of the adding a single anti-phased burst to a conventional sampled grating DBR. Proper positioning of the anti-phased burst can be used to flatten or modify the conventional spectra.

Fig. 6 illustrates a manipulation of the sampling function that leads to a more desirable multi-peaked sampled-grating reflector, by reversing the phase of the sampling function at the beginning and end of each burst.

Fig. 7 (a) & (b) illustrate an example of using the modified sampling function to give a wider wavelength range than the conventional sampling function.

Fig. 8 (a) & (b) illustrates an example of using the modified sampling function to give an increase in the κ of the sampled grating mirror over the same wavelength range as the conventional sampling function.

INS A2

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the following description, reference is made to the accompanying drawings which form a part hereof, and in which is shown, by way of illustration, an embodiment of the present invention. It is understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

SUB A1

Figure 2 depicts a widely-tunable, four-section SG-DBR laser 10 that makes use of two multi-peaked DBR mirrors 12,14, which are formed and configured in accordance with the present invention, to achieve an extended tuning range. Currents are applied to the various electrodes to provide a desired output optical power and wavelength as discussed in US Patent #4,896,325. As described therein, a current to the gain section 16 creates light and provides gain to overcome losses in the laser cavity; currents to the two differing SG-DBR wavelength-selective mirrors 12,14 are used to tune a net low-loss window across a wide wavelength range to select a given mode; and a current to a phase section 18 provides for a fine tuning of the mode wavelength. It should also be understood that the sections 12,14,16,18 are somewhat interactive, so that currents to any will have some effect on the parameters primarily controlled by the others.

An example of the mirror spectra from a conventional pair of mirrors, without the improved configuration, is shown in Figure 2. Mathematically, the sampled grating can be thought of as the multiplication of a grating function and a sampling function, as illustrated in Figure 3a and 3b. In the conventional design, the sampling function can only have the value of +1 or 0, due to the technological method used in fabrication. The grating function is also technologically limited to κ's less than 300 cm^{-1}, to prevent optical scattering.

Examining Figure 3, the Fourier transform relation between the square sampling function of the conventional SG mirror and its sinc function envelope of reflectivity peaks is clearly obvious. Modification of the sampling function to tailor the frequency response of

the peak envelope is well known to those skilled in the art. In the case of the SG-DBR to be produced with a phase mask, the sampling function can only take the value of 0,1 or –1, with –1 indicating a phase reversal of the grating function.

The phase mask technology for printing gratings, allows the sampling function to take on a value of +1, 0 and –1, with a manufacturable process that can be used to create sampled grating. Phase masking is well known to those skilled in the art, although this application is new. This invention relates to using this added degree of freedom offered by current phase masking technology to tailor the spectrum of the SG-DBR wavelength-selective mirrors to improve the laser performance.

An embodiment of this invention can be as simple as adding a single anti-phased burst at the beginning of the grating as shown in Figure 4. Properly positioned, this burst can flatten the multi-peaked reflectivity spectrum, or make the reflectivity larger at the edges, as shown in Figure 5. These examples are very simple, and more sophisticated tailoring can be achieved identifying the analog sampling function that produces the desired effect and digitizing it using the strategies commonly employed in digital sampling applications.

SUB A4

Another sampling function is shown in Figure 6. Reversing the phase of the grating at the beginning and end of each sample can be used to tailor the peak envelope to allow for higher kappa over a larger range. Figures 7a and 7b illustrate an example of the peak envelopes that would result from the modification discussed in Figure 6, showing that the modification produces the intended effect: a mirror with a wider wavelength range **and** with a larger throughout.

Figures 8a and 8b show a similar application of the sampling function that produces a mirror with twice the κ over the same tuning range with a much flatter envelope. A more sophisticated and powerful embodiment is to use the phase mask capability to tailor the sampling function to achieve the desired mirror peak spectrum.

Figures 7 and 8 show specific modifications to the sampling function used to create sampled-grating mirrors that cover a larger wavelength range and have higher reflectivity than the conventional approach. However, those skilled in the art can manipulate the sampling function within the constraints of the phase mask technology to produce a wide

range of desirable changes to the conventional approach. Additionally, as phase masking technology improves, the precision with which one may refine the sampling function will improve as well.

A method to select the configuration of a mirror 12,14 and therefore an associated sampling function, is to a) select a preferred κ for the wavelengths of a specific region of the band(s) that are to be used, b) select a preferred tuning range, c) using a sampling function that, when applied to the laser's output, results in the closest fit to the desired κ and output powers.

INS A3

It is important to realize that one of the advantages of the sampled grating mirrors is that the areas without grating are technologically easier to produce with high tuning efficiency and reliability, as they have no etch damage and less exposed surface area. Therefore, it is desirable that the grating areas (regardless of its phase) occupy only a fraction of the entire mirror.

There are several advantages of this invention over the mirrors disclosed in the prior art. One of the biggest advantages is that the phase between the sampling function and the grating function need not be preserved, allowing the required phase mask to be fabricated with simply holography. In addition, all of the other methods accomplish the peak tailoring through the use of a modified grating that covers the entire surface of the waveguide, whereas this invention preserves the fact that the grating occupies less than 30% of the entire SG mirror. This is very important because it has a direct impact on the tuning efficiency of the mirror. During the fabrication of multi-peaked mirrors the process introduces crystal damage in the grating due to both etching and regrowth. This crystal damage reduces both tuning efficiency and lifetime of the widely tunable laser using these mirrors. It is much easier to produce a damage free surface in waveguide areas without grating, and SG-DBR's were shown to have superior tuning performance over other forms of widely tunable lasers with continuous gratings. Therefore, using the sampling function approach to modify the mirror spectrum is advantageous.

The foregoing description of one or more embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.